Microengineered Optical Scanner

5   Field of the Invention
The invention relates to optical scanners and in particular
to a microengineered optical scanner or optical reading
device and methods for making such a device.

10 Background

Bar code readers and scanners are optical information
gathering systems. They operate by sweeping a point image
through a set of trajectories and using confocal detection
15 to collect light back-scattered from objects present in the
focal plane. In a point-of-sales (POS) application, the
object is a coded bar pattern, which provides brand and
category information on an item to be sold. Other
applications include inventory control and video
20 programming. In many of these applications, it is important
that the scanners be portable and lightweight, and allow
hands-free operation. There is therefore a strong incentive
to reduce their size and cost.

25 There are several methods of generating the scan line in a
bar code reader. A static point image may be created, simply
by using a lens to form a real image of a point source.
Alternatively, a curved, focusing mirror may be used. This
image may be converted into a dynamic image by moving one of
30 the components in the system. Scanning by motion of the
source (100), with a lens (105) held fixed, generates a
continuous scan line (110), as shown in Figure 1a. Scanning

by selecting one of a number of discrete sources (115) generates a discrete scan line (120), as shown in Figure 1b.

Scanning by moving the lens again generates a continuous scan line, as shown in Figure 1c. In this case, an array of lenses (125) is often swept past the source (130) in sequence. The lenses may be constructed as an arrangement of flat, holographic elements on a disc, which is then rotated to provide the necessary lens motion.

The scanner types described above are known as 'pre-objective' scanners, since they exploit the motion of an object in front of an objective lens. An alternative group are known as 'post-objective' scanners. These involve deflection of the beam by a mirror (135) after the imaging system, as shown in Figure 1d. The beam may be deflected by rotation of a polygonal mirror, or a mirror mounted on an elastic torsion suspension. Torsion mirrors are often resonant vibrating devices.

The signal is obtained from back-scattered light. To obtain sufficient signal strength, the back-scattered beam must normally be of considerably higher numerical aperture than the illuminating beam. To reject ambient light and signals from de-focused objects, confocal detection is often used. This method may be implemented using an additional beam-splitter (140), pinhole (145) and photodiode (150) as shown in Figure 1e. Clearly the position of components such as the beam-splitter and photodiode must remain fixed relative to the source if the detected signal is to track the scanned image point. This requirement can easily be satisfied using fixed component positions in moving lens or moving mirror systems. It is harder to satisfy in a moving source system.

A number of the techniques described above have been
miniaturised using micro-electro-mechanical systems (MEMS)
technology. This method involves the use or adaptation of

5   semiconductor processing to form a variety of structures and
devices in addition to conventional electronic components.
Often the materials are silicon and its compatible oxides.
Examples of micro-electro-mechanical systems include
mechanical, thermal, fluidic, chemical, biochemical,

10 electrical and optical systems.

A number of MEMS based scanners have been described or
constructed. However, the vast majority lack any appropriate
signal detection, and are therefore not true reading

15 systems. For example US 5 734 490, describes the
construction of a MEMS scanner as a moving lens systems.
MEMS-based polygonal scanners have also been constructed by
using deep reactive ion etching to create mirror surfaces
that lie normal to the substrate.

20

However, the overwhelming emphasis has been to use shallower
etching methods to create mirror surfaces that lie parallel
to the substrate. These have been implemented as single-axis
torsion mirror scanners such as that described in US 4 317

25 611 and also as two-axis devices as described in US 5 629
790. Alternatively as described in EP 0 875 780, MEMS mirror
scanners have used beam bending rather than torsion. Two-
axis vibrating beam scanners have also been demonstrated in
patents such as US 5 097 354 and US 5 444 565, which also

30 have incorporated signal detection.

The most complicated MEMS moving mirror scanners have used
surface micro-machining methods to create sets of flat

parts. The parts are subsequently rotated out of plane and
interlocked to form fully 3D structures. Such a device is
disclosed by Syms R.R.A. "Operation of a surface-tension
self-assembled 3-D micro-optomechanical torsion mirror
5   scanner" Elect. Lett. 35, 1157-1158 (1999).

MEMS-based moving source scanners have received less
attention, because of the difficulty of constructing a
suitable confocal detection system.
10

The principle of optical scanning by vibrating a
cantilevered fibre and the application of an optical fibre
receiver to a bar code reader have both been described in
patents such as US 5 404 001, US 5 422 469 and US 5 521 367.
15   Figure 2a shows the former process. A length of fibre (205)
is mounted so that a short section protrudes from an anchor
point (210). This section may be excited into mechanical
oscillation using a cantilever (215) at the resonant
frequency for bending mode vibrations. Laser light (200)
20   injected into the fixed left-hand end will then emerge from
the moving right-hand end to form an illuminating beam
(230). The moving source thus created is then imaged onto
the bar code (240) by a lens (220). Figure 2b shows the
latter process. Back-scattered light (233) from the bar code
25   is coupled back into the fibre (205) , and passed to a
detector (255) by a beam splitter (245) . An optical fibre
coupler (250) may be used instead of the beam splitter as
shown in Figure 2c.

30   The light that is transmitted by a dielectric waveguide
(300), such as an optical fibre, is guided by total internal
reflection at the interface (325) between the central core
(305) and the surrounding cladding material (310), as shown

in Figure 3a. Because the refractive indices of the core and
cladding are normally quite similar, total internal
reflection only occurs when the light rays strike the core-
cladding interface at a shallow angle. The light emerging
5   from the end facet (315) of a single-mode optical fibre
therefore has a very low numerical aperture (NA), and forms
a narrow cone of radiation. After magnification by a lens,
as shown in Figure 4, the cone of radiation falling on the
bar code has an even smaller NA. This can be advantageous
10   for scanning, since it results in a large depth of focus.
However, it results in a low detected signal, because only a
small fraction of the available back-scattered light is
collected. The useful range of a bar code reader constructed
in this way is therefore small.
15

The light that is guided in the cladding of the optical
fibre may have a much larger numerical aperture, since the
difference in refractive indices of the cladding and the
surround (air) at that interface (330) is normally much
20   greater. In principle, a much larger fraction of the back-
scattered light (320) may therefore be gathered if it is
coupled into the cladding of the fibre as shown in Figure
3b. The cladding mode light may be extracted from the fibre
by, for example, cementing the fibre to a slab (340) using
25   an index-matched epoxy (335), as shown in Figure 3c. The
slab may be a detector element, allowing direct detection of
the cladding mode light.

This principle allows a confocal system to be constructed
30   with different numerical apertures for the illuminating beam
and the received signal, as shown in Figure 4. Here the
illuminating beam (410) is derived from the guided mode of a
single-mode optical fibre (300), and forms a low numerical

aperture beam that is imaged by the lens (400) onto the
surface (405) to be scanned. The received signal (415) is
collected by the same lens and coupled into the cladding
modes of the same fibre. Some light is necessarily coupled

5   back into the guided mode, but this represents a small
fraction of the total. The cladding mode light may be
conveniently separated from the guided mode using a mode-
stripping detector as described earlier, without the need
for an additional beam splitter.

10

A fibre-based dual numerical aperture bar code reader
operating in this way has previously been described by the
present inventors in Roberts D.A., Syms R.R.A., Holmes A.S.,
Yeatman E.M. "Dual numerical aperture confocal operation of

15 a moving fibre Bar code reader" Elect. Lett. 35, 1656-1658
(1999), and Roberts D.A., Syms R.R.A. "1D and 2D laser line
scan generation using a fibre optic resonant scanner"
SPIE Proc. 4075, 62-73 (2000). It was shown that the
improvement in signal collection efficiency allowed a

20 considerable increase in the range over which the system
could be operated, compared with a comparable system based
on collection of back-scattered light into the guided mode.

However it was also shown that the magnification of the lens

25 has a significant effect on performance and that the
requirements on magnification for detection and scanning are
therefore in conflict.

Two types of MEMS actuators are common; those based on

30 electrostatic operation and those based on electrothermal
operation. Typical MEMS electrostatic actuators (500)
consist of either parallel or interdigitated electrodes
(520), such as those shown in Figure 5a. Each type may be

formed by etching a pattern into an electrically-isolated
silicon or poly-silicon layer. The layer may then be
metallised to improve its conductivity. Application of a
voltage from a voltage source (505) to two anchors (510a)

5   coupled to the electrodes then gives rise to an attractive
electrostatic force. Interdigitated electrodes typically
offer greater capacitance, and hence greater force, in a
given chip area. Application of a voltage between the
electrodes results in an electrostatic force, which deflects

10   the cantilever laterally until the elastic force of the
cantilever balances the electrostatic force.

MEMS electrothermal actuators typically consist of buckling
mode devices and bimorphs, and examples are shown in Figures

15   5b and 5c. A current is passed through a beam (525) that is
suspended between two anchor points (510b, 510c).
Constrained thermal expansion results in an axial force,
which buckles the beam laterally when the first Euler
critical load is reached. The force obtained can be

20   increased, by using a set of actuators arranged in parallel.
The direction of buckling (which is indeterminate in the
symmetric system shown) may be preferentially determined by
using a pre-buckled beam shape or an eccentric load.

25   Electrothermal bimorphs can be divided into two types, based
on differences in material and shape, respectively. The
former requires additional layers of material. Figure 5c
shows an example of the latter. A folded beam, having a hot
arm (530) and a cold arm (540) is suspended between two

30   anchors (510c). The beam has a variable cross-sectional
width, being narrower on average in one of the two arms (the
hot arm) than the other (the cold arm). When a current is
passed between the anchors, the hot arm is preferentially

heated and therefore expands more. Differential thermal
expansion then deflects the structure laterally. A flexure
(580) is placed at the root of the cold arm (540) to allow
motion. Similar behaviour can be obtained using unequal arm
5   lengths, or a doubled hot arm.

MEMS actuators typically provide only small displacements.
Much larger displacements may be obtained by coupling the
actuator (560) to a resonator (565), such as a long
10   cantilever as shown in Figure 5d. Out-of-plane actuators
have been constructed in this way using material bimorphs,
and in-plane actuators have been constructed using shape
bimorphs such as those described in Syms R.R.A. " Long-
travel electrothermally-driven resonant cantilever
15   microactuators" J. Micromech. Microeng. 12, 211-218 (2002)).

The actuator consists of a long cantilever coupled to an
electrothermal drive and lateral displacements of 0.5 mm
were obtained at low powers when the resonant frequency of
20   the cantilever was appropriately matched to the bandwidth of
the transducer, and when the cantilever was sufficiently
massive to obtain a resonance with high quality factor. This
displacement has been shown to be sufficient for bar code
reading applications.
25
Despite these advances, little progress has been made in
developing an integrated pre-objective scanner. There is
therefore a need to provide a device that meets the
performance requirements of a bar code reader yet can be
30   provided in a MEMS environment.

It is an object of the present invention to provide such a
device and a method of manufacturing same.

Summary of the Invention

5   Accordingly the present invention provides a Bar code reader device or scanner fabricated using silicon-based micro-electro-mechanical systems (MEMS) technology.

     In accordance with a preferred embodiment of the invention
10   an optical reading device is provided having a light source, a movable optical waveguide, an actuator, a detector. The actuator and detector are desirably integrally formed in a substrate, the movement of the waveguide being effected by action of the actuator thereon.
15
     Typically the device further includes motion sensors such that any movement of the waveguide is detectable by the motion sensors.

20   The optical waveguide is desirably formed as an integrated channel guide formed in dielectric materials and surrounded by a cladding of restricted lateral dimensions.

     Alternatively, the waveguide may be externally attached or
25   coupled to the device.

     Typically, the optical waveguide is single-moded and polarization-preserving.

30   Preferably, the source is polarized and arranged to excite a single polarization mode of the waveguide.

In a preferred embodiment the optical waveguide is
constructed on a suspended cantilever above a substrate. In
a first embodiment the waveguide is supported by a
mechanical layer along its entire length. In an alternative
5   embodiment the waveguide is supported only near its root by
a mechanical layer.

Desirably the substrate provides a mechanical layer, and is
typically a silicon based layer. In one embodiment the
10   detector is constructed in the silicon layer as a p-n
junction or p-i-n junction photodiode.

Desirably, the detector is placed beneath the waveguide to
detect cladding modes present in the waveguide.
15

Typically the detector is a photodetector and is placed or
formed at the tip of the cantilever. Alternatively, the
photodetector is placed near the root of the cantilever.

20   In a first embodiment the actuator is placed near the root
of the cantilever. Typically the actuator is constructed as
an electrothermal or electrostatic drive.

In one embodiment the actuator is an electrothermal shape
25   bimorph actuator. In a first embodiment the waveguide is
placed over the cold arm of such an electrothermal shape
bimorph actuator.

In an alternative embodiment the electrothermal shape
30   bimorph actuator has dual hot arms.

The electrical current in the cold arm is desirably
monitored and suppressed using an active feedback circuit.

This is advantageous in reducing the pick up of un-wanted noise, with the effect that the lower the noise the greater the range of operation of the device.

5   The motion sensors are typically placed near the root of the cold arm and the root of the cantilever. This assists in maintaining the known scan amplitude which may otherwise be difficult to monitor. These may be constructed as piezo-resistive or capacitative devices or some other suitable
10   type detector.

Typically, the motion sensors are constructed as pairs of piezo-resistors, arranged to detect differential strain caused by bending of the structure and may be connected to a
15   differential readout circuit.

According to another embodiment of the present invention an optical reading system comprises a device having one or more of the following components:
20   1) a cantilevered single-mode optical waveguide suitable for transmitting light onto a target thereby illuminating the target and adapted to effect a reception of the back-scattered signal from the target into the cladding of the waveguide,
25   2) an actuator capable of achieving large in-plane displacement,
     3) motion sensors capable of providing the necessary signals for closed loop control of the scan amplitude,
     4) a cladding mode detector capable of implementing a
30   confocal detection system so as to effect a detection of the light backscattered into the cladding of the waveguide

5) a lens, which may be formed in the wall of the device
   package, and
   the device being coupled to
   a laser source, which may be hybridised or integrally
5 formed with the device of the present invention or linked
   thereto by a section of optical fibre so as to provide
   the incident light to the waveguide.

Desirably the elements 1 - 5 may all be fabricated in
10 silicon-based materials using a compatible process. It will
be appreciated that alternative materials such as gallium
arsenide may also be considered as alternatives for the
substrate material. This process also has the potential to
allow the integration of the electronics for drive, sense
15 and detection. The integration scheme of the present
invention offers advantages of cost and size reduction,
increased reliability, and improved optical and electrical
performance.

20 Applications of the invention include miniature, portable or
hands-free bar code readers for point-of-sale scanning,
inventory control and video programming, and devices for
inspection of confined spaces or similar medical
applications such as endoscopy.
25
The present invention also provides a method of providing an
optical reader comprising the steps of:
        forming a detector in a substrate,
        optically coupling a waveguide to the detector, and
30   effecting the formation of a cantilever coupled to the
waveguide and adapted to effect a movement of the waveguide
upon stimulation, and

wherein the cantilever and detector are integrally formed in the substrate, the waveguide being adapted to transmit light onto a target and receive light backscattered from the target, the light received back into the waveguide being
5   detectable using the detector.

These and other features of the present invention will be better understood with reference to the following drawings.

10   **Brief Description of the Drawings**

Figure 1a shows a conventional bar code reader utilising scan by source motion,
Figure 1b shows a conventional bar code reader utilising
15   scan by source selection,
Figure 1c shows a conventional bar code reader utilising scan by lens motion,
Figure 1d shows a conventional bar code reader utilising scan by mirror deflection,
20   Figure 1e shows a conventional bar code reader utilising scan by confocal detection,
Figure 2a is a prior art moving fibre bar code reader utilising the generation of a scan line by a vibrating optical fibre cantilever,
25   Figure 2b is a prior art moving fibre bar code reader which provides for the detection of back scattered light using a beam splitter as a tap,
Figure 2c is a prior art moving fibre bar code reader which provides for the detection of back scattered light using a
30   fibre coupler as a tap,
Figure 3a is a ray model showing optical wave guidance in a dielectric waveguide,

13

Figure 3b is a ray model showing a cladding mode in a
dielectric waveguide,

Figure 3c is a ray model showing cladding mode stripping in
a dielectric waveguide,

5   Figure 4 is an example of the principle behind a prior art
dual numerical aperture moving fibre bar code reader,

Figure 5a is a prior art MEMS actuator based on
interdigitated electrostatic operation,

Figure 5b is a prior art MEMS actuator based on buckling

10   mode electrothermal operation,

Figure 5c is a prior art MEMS actuator based on shape
bimorph electrothermal operation,

Figure 5d is a prior art MEMS actuator based on excitation
of a cantilever resonator by a shape bimorph,

15   Figure 6a shows a side and plan view of an arrangement of a
waveguide, driver and detector for a supported waveguide
according to the present invention,

Figure 6b is side view of an arrangement of a waveguide,
driver and detector for a supported waveguide with the

20   substrate removed according to the present invention,

Figure 6c shows a side and plan view of an arrangement of a
waveguide, driver and detector for an unsupported waveguide
according to the present invention,

Figure 7a is a section along the line A-A of Figure 6a

25   showing an optical waveguide and cladding mode detector
integrated into the substrate,

Figure 7b is a section along the line B-B of Figure 6c
showing an externally attached waveguide,

Figure 8a is a plan view of a cantilever tip,

30   Figure 8b is a view of a circuit adapted to connect a
photodiode to a transimpedance amplifier,

Figure 9a is an arrangement of an integrated scanner incorporating an electrothermal shape bimorph drive with dual hot arms,

Figure 9b is an integrated scanner having an arrangement of
5   sensors and contact pads,

Figure 10a shows drive electronics for an integrated scanner including a simplified drive arrangement with a floating source,

Figure 10b shows an alternative arrangement with active
10 suppression of the residual current in the cold arm,

Figure 11a shows a plan view of a device according to the present invention showing the positioning of motion sensors near the actuator root,

Figure 11b is a view showing the positioning near the
15 cantilever root,

Figure 11c shows an example of circuitry providing connection to readout circuit,

Figure 12 shows a plan view of the routing for contact metallisation,

20 Figure 13 is a process flow shows steps associated with the formation of a device according to the present invention, and

Figure 14 details in successive steps more detail associated with the manufacture of an integrated device according to
25 the present invention.

Detailed Description of the Invention

Figures 1 to 5 have been described previously with reference
30 to prior art implementations.

The present invention will now be described with reference to Figures 6 to 14.

Figure 6 shows an integrated optical reader according to the present invention. The optical detection device provides an actuator (640) for effecting movement of a optical waveguide

5   (630) and a detector (635) for detecting the light, which is predominately backscattered light. Both are integrally formed in a substrate (605). In a preferred embodiment a movement of the waveguide is provided by coupling the waveguide to a cantilever and actuating the cantilever to

10   effect an associated movement of the waveguide. Desirably the detector is adapted to detect the cladding mode components of a waveguide. Preferably these components of the optical detection device are combined with a light source, a waveguide and motion detectors.

15

We now give a detailed description of the invention, considering in turn aspects of the source, waveguide and cantilever, cladding mode detector, actuator and motion sensors.

20

We first consider the source. We assume for the purposes of pointing the device that a visible source is required, although it will be appreciated that the source can be chosen dependant on the application of the device. To obtain

25   sufficient power coupled into the waveguide, the source will typically be a laser constructed in III-V materials with an appropriate bandgap. It will be appreciated by the person skilled in the art that either a conventional stripe waveguide laser or a vertical cavity surface emitting laser

30   (VCSEL) will typically be most suitable. Known techniques exist for attaching an optical fibre pigtail to either type of laser. The fibre pigtail may be used directly as the waveguide element of the scanner, as described later.

Alternatively, the fibre pigtail may be butt-coupled to a
different optical waveguide that forms an integral part of
the scanner. Finally, an un-pigtailed laser may be butt
coupled to an integrated waveguide, and attached to the
5   substrate by flip-chip bonds.

We now consider the integrated parts of the device. Because
silicon itself is not transparent at visible wavelengths,
the waveguide must be formed from other materials. These
10   materials must be of sufficient thickness that the guided
light is held away from any regions supported by a silicon
substrate, so that optical propagation losses remain low.
Suitable transparent, silicon compatible materials include
but are not limited to Si_3N_4, SiO_2, silicate glasses (i.e.,
15   SiO_2 doped with compatible oxides), and other deposited
oxides. Suitable deposition processes for these materials
include vacuum evaporation, sputtering, chemical vapour
deposition (CVD), plasma enhanced chemical vapour deposition
(PECVD), flame hydrolysis deposition (FHD) and the sol-gel
20   process.

It will be appreciated that not all processes can achieve
large deposited thickness'. Thin dielectric layers may still
be used, provided the refractive index step between the core
25   and the cladding is sufficiently large that the guided mode
is confined well away from the substrate.

If thin layers are used, the waveguide must be supported by
an additional mechanical structure along its entire length.
30   A suitable structure can be provided using bonded silicon-
on-insulator (BSOI) material. BSOI consists of an oxidised
silicon substrate, to which is bonded a second silicon
substrate. The bonded substrate may then be polished back to

17

leave a desired thickness of silicon. Other methods of
constructing similar substrates exist. The upper silicon
layer may be patterned and etched to define mechanical and
other parts, using standard MEMS processes. The oxide layer
5   may then be removed from beneath the mechanical parts to
allow motion.

Using BSOI material and suitable dielectric layers, a
waveguide cantilever (630) having a mechanical support along
10   its entire length may be constructed as shown in Figure 6a.
The bonded silicon layer (610) provides the support, and the
oxide interlayer (615) is removed from beneath the
cantilever (630) except at the anchor (625) to allow motion.

15   Because the deposited dielectric layers (625) are often
stressed, the cantilever may be distorted from the ideal
straight, linear geometry. If the dielectric layers are
under compressive stress, it may be deflected downward
towards the substrate. In this case, the substrate (605) may
20   be removed from beneath the cantilever as shown in Figure
6b. This geometry allows additional clearance, and the
possibility of depositing additional layers of dielectric on
the base of the cantilever to apply a counterbalancing
stress.
25
The bonded layer (610) may also be removed from beneath the
waveguide (630), as shown in Figure 6c, so that the majority
of the suspended structure is a free-standing dielectric
cantilever without an additional mechanical support. A
30   similar geometry is provided by attaching a separate
dielectric waveguide (750) (such as an optical fibre) to
suspended MEMS parts (for example, using index-matched
epoxy).

An integrated dielectric optical waveguide is desirably
formed as a three-layer structure as shown in Figure 7a. The
three layers comprise:

5

1) A buffer layer (725) of lower index dielectric, which
   isolates the guided mode from the silicon substrate,
2) A core (700) of higher-index dielectric, which is etched
   into a cross-section of dimensions suitable for single-
10   mode operation
3) A cladding (720) of lower-index dielectric, which is
   deposited over the patterned core.

After deposition of the cladding layer, the whole structure
15 is etched down to the silicon surface to provide a cladding
of defined lateral dimension. The lateral dimension will
typically be large enough to isolate the guided mode from
the edge of the cladding. However, it will not be so large
as to increase the area from which back-scattered light is
20 gathered by an unwarranted amount.

Alternatively, in a hybrid integrated device, the waveguide
may be provided externally (for example, as an optical fibre
pigtail (750)) and attached to the other MEMS parts using
25 index-matching epoxy (760)as shown in Figure 7b.

In order to avoid interference effects between different
modes of propagation, the waveguide is desirably single-
moded. However, even single-mode waveguides support two
30 different modes, one for each possible polarization of
light. Interferometric effects may still arise if both
polarization modes are launched, and if the motion of the
waveguide gives rise to time-varying phase shifts between

them. For this reason, the waveguide is therefore desirably
asymmetric, so that the two polarization modes are distinct.
It is also desirable that the source is polarized, and has
its polarization axis orientated such that only one
5 polarization mode is coupled into the waveguide.

The cladding mode detector (715) may be a p-n or p-i-n
photodiode, formed in the bonded silicon layer using
standard methods of in-diffusion of p- and n-type dopants,
10 and arranged to lie beneath the dielectric waveguide as
shown in Figure 7a. Although silicon is not a direct gap
material, such a detector will be entirely appropriate for
visible light.

15 For example, the support cantilever (805, 810) may be
fabricated in p-type semiconductor (825), as shown in Figure
8a. A p-n photodiode may then be formed in this layer, by
first creating a deep n-type well (815) and then a shallow
p-type well (820). An additional isolation layer (710, in
20 Figure 7)of lower-index dielectric may be deposited over the
waveguide (805)and etched to provide via holes through to
the p-well and the n-well.

Contact metallisation (800) may then be deposited and
25 patterned to allow ohmic connection to the detector (715).
The contact tracks may be taken along the cantilever to its
root for connection to suitable electronics. The photodiode
current I_{PD} may be detected using a transimpedance amplifier
circuit, as shown in Figure 8b. Here a positive DC bias V_5
30 is applied to the contact to the n-well (815), to maintain
the photodiode (PD1) under reverse bias.

If the cantilever (810) potential is held near to ground,
the p-n diode formed between the n-well (815) and the
cantilever will also be under reverse bias, thus providing
effective electrical isolation between the photodiode and
5   the cantilever. This isolation will also apply to the other
sensor components, as described later.

Because the presence of a silicon substrate beneath the
dielectric waveguide will result in the rapid absorption of
10 cladding mode light, the optimum position of the cladding
mode detector is different in the geometries of Figures 6a
and 6c. In Figure 6a, the cladding mode detector (635) must
lie at the tip of the cantilever. In Figure 6c, it must lie
near the root. This choice of positioning of the detector
15 (635) is effected based on the structure of the device.
However, cladding light will still be directed along the
waveguide to the detector by total internal reflection at
the cladding-air interface.

20 To obtain sufficient lateral deflection, the waveguide is
typically arranged as a long, relatively massive cantilever,
driven at its root by an actuator (640). Because they simply
require the fabrication of additional etched features,
electrostatic and electrothermal MEMS actuators may each be
25 integrated with the suspended cantilever very simply.

In the case of an electrostatic actuator, an interdigitated
electrode structure is most suitable. The waveguide should
ideally be mounted above the grounded arm, to minimise the
30 effect of voltage fluctuations.

In the case of an electrothermal actuator, a shape bimorph
is most suitable, as it induces bending and therefore can be

used to effect better actuation of the cantilever and
associated waveguide. As shown in Figure 9, the waveguide
(630) should ideally be mounted above the cold arm (915), to
minimise the effect of temperature variations. To reduce the
5   heating of the cold arm as much as possible, the actuator
then desirably has a dual hot arm (905, 910) as shown in
Figure 9a. The heating current is passed between the
terminals 1 and 2 of the two hot arms in Figure 9b so that
direct resistive heating of the cold arm is avoided.
10

In order to reduce electrical cross-talk between the drive
and the various sensors, the potential of the cold arm
should be held as close to ground as possible. The terminal
3 to the cold arm may be grounded, and the actuator may be
15   driven using a floating voltage source V_{12} as shown in
Figure 10a. R_{h1} and R_{h2} are the resistances of the two hot
arms.

If there are no parasitic currents, then no current will
20   flow through the resistance R_c of the cold arm and the cold
arm will be at ground. In general, it will be appreciated
however that, there will be parasitic current paths to
ground, both from the source and from the circuit elements.
These may lead to a small residual current in R_c and hence
25   an unwanted AC voltage in the cold arm. The amplitude of
this voltage will vary along the cold arm from zero at
terminal 3 to a maximum at point X, remaining at this
amplitude along the cantilever. This voltage may be coupled
undesirably to the sensor elements (920, 925).
30

In over to overcome such variances it is possible to modify
the drive, an example of which is shown in the improved
drive of Figure 10b. Here the residual current in the cold

22

arm is monitored by a transimpedance amplifier connected to
terminal 3, and actively suppressed by a closed loop
controller using two separate AC voltage sources V_1 and V_2.

5   To establish a closed-loop control of the scan amplitude,
the mechanical motion of the actuator and the cantilever
must be monitored. A measure of the actuator and cantilever
deflection may be obtained by using piezo-resistive or
capacitative sensors. The former may be integrated during
10   one of the diffusion steps used to fabricate the photodiode,
and the latter during construction of the actuator.

Figure 9b shows suitable locations for piezo-resistive
sensors, at the root (920) of the cold arm and the
15   cantilever (925). Figures 11a and 11b show how these sensors
may be constructed as p-type resistive channels (PR_{1b}, PR_{1a},
PR_{2a}, PR_{2b}) in an n-type well formed in a p-type layer,
using similar diffusion processes as Figure 8a.

20   In order to minimise the sensitivity to temperature, two
piezo-resistors are used at each location. At the root of
the cold arm, the piezo-resistors are PR_{1a} between contacts
6 and 7, and PR_{1b} between contacts 7 and 8. At the root of
the cantilever the piezo-resistors are PR_{2a} between contacts
25   9 and 10, and PR_{2b} between contacts 10 and 11.

At each sensor location, the two piezo-resistors experience
similar temperatures T. However, because they are located
near opposite edges of the mechanical structure, they
30   experience opposite stresses when the structure is bent
laterally. The common mode signal caused by temperature
variations may therefore be rejected in favour of the signal
due to bending, by using a differential readout.

A suitable differential readout circuit for the actuator
motion sensor may be based on a resistive bridge, as shown
in Figure 11c. The circuit required for the cantilever
5   motion sensor is similar. In this configuration, equal bias
currents are applied to the two piezo-resistors using a bias
voltage V_{BIAS} and series resistors R_a and R_b. The difference
between the resulting voltages is measured using a
differential amplifier.
10

In the complete system, electrical contacts are taken to the
electrothermal drive (from terminals 1, 2 and 3), the
photodetector (from terminals 4 and 5), the actuator motion
sensor (from terminals 6, 7 and 8), and the cantilever
15   motion sensor (from terminals 9, 10 and 11). The first three
contacts are made directly to the bonded silicon layer. The
remainder should typically be routed to their relevant
locations using patterned metal tracks. Figure 12 shows a
simple arrangement for routing the contact metallisation on
20   either side of the waveguide.

Figure 13 is a simplified process flow to be read in
combination with Figure 14 and outlines the process flow
according to one embodiment of the present invention for
25   forming a device according to the present invention. In
steps 1 and 2 of Figure 14 the detectors are formed in the
silicon substrate. Steps 3-6 are concerned with the
formation of a waveguide in the substrate. Steps 7 and 8
relate to the formation of electrical contacts to external
30   drive and sensing circuitry whereas Steps 9 and 10 relate to
an etch process which is undertaken so as to form the
cantilever. These steps are outlined in more detail in
Figure 14 which shows an example of a wafer-scale process

for fabrication of a set of dies, each comprising an
integrated scanner containing the elements described above.
The starting material is a bonded silicon-on-insulator wafer
with a p-type bonded Si layer. Variations of the processes

5   shown, and also of the exact sequence in which they are
performed, may be used to create similar structures, as will
be appreciated by those skilled in the art and it is not
intended to limit the process flow of the present invention
to any specific sequence or operation of steps.

10

The p-n junction photodetectors and piezoresistors are
formed in Steps 1 and 2. In Step 1, the wafer is oxidised,
and the first oxide layer is patterned by lithography and
then etched to provide openings for all the n-wells. The n-

15   wells are desirably formed by a deep diffusion, and the
first oxide mask is removed. In Step 2, the wafer is re-
oxidised, and the second oxide layer is patterned by
lithography and then etched to provide openings for all the
p-wells. The p-wells are formed by a shallow diffusion, and

20   the second oxide mask is removed.

The waveguides are formed in Steps 3 - 6. In Step 3, a glass
bilayer is deposited on the wafer. The glass compositions
are chosen so that the upper layer has a higher refractive

25   index than the lower layer, so that a waveguide is formed.
The thickness of the upper glass layer is chosen so that it
can act as the core of a single mode buried channel guide.
The thickness of the lower glass layer is chosen so that the
evanescent field of the guided mode has decayed sufficiently

30   by the time it reaches the bonded silicon layer that low
propagation loss may be obtained. In Step 4, the upper glass
layer is patterned by lithography and then etched into
narrow strips, which can act as the cores of buried channel

guides. In Step 5, a further glass layer is deposited on the wafer. The glass composition is chosen so that it has a lower refractive index than the core glass, and can therefore act as a cladding for the cores. In Step 6, the

5   wafer is patterned by lithography and then etched to remove the cladding and buffer layer glass from everywhere except in narrow strips surrounding each buried core.

The electrical contacts are formed in Steps 7 and 8. In Step
10   7, a further glass layer is deposited on the wafer. This layer may be similar to the cladding glass; however, it now has the function of electrical isolation. This layer is patterned by lithography and then etched to provide windows through which electrical contact may be made to the diffused
15   wells, and also to the bonded silicon layer itself. In Step 8, metal layers suitable for making ohmic contacts to the diffused wells and to the bonded silicon layer itself are deposited over the wafer. These layers are patterned by lithography and then etched to form a set of connecting
20   tracks.

The mechanical parts are formed in Steps 9 and 10. In Step 9, a layer of durable material is deposited over the wafer. This layer is lithographically patterned, and then used as a
25   hard mask in a deep etching step. In this step, trenches are etched right through the bonded silicon layer, to define the mechanical parts of the structure. One suitable process for this step would be deep reactive ion etching using an inductively coupled plasma etcher. The hard mask is then
30   removed. In Step 10, the rear of the wafer is removed from beneath the movable mechanical parts, together with the oxide interlayer. One suitable process for this step would be deep reactive ion etching from the rear of the wafer.

Following these processes, the wafer is separated into
individual dies, each containing a scanner component. The
dies are individually packaged, and wirebond connections are
5   made to the electrical contact pads. Depending on the exact
mode of operation, a laser source is then either coupled
directly to the channel waveguide or coupled indirectly
using a linking section of optical fibre.

10   Accordingly the present invention provides a microengineered
optical scanner based on a moving cantilevered dielectric
waveguide. The waveguide is typically excited into resonant
mechanical motion by a drive, desirably located at its root.
Stress sensors may be provided to detect the bending of the
15   waveguide, thereby allowing closed loop control of the
motion. A moving image of the light emitted from the moving
tip of the waveguide is created by a lens. The moving image
acts as a scan line. Light back-scattered from a rough
surface placed at the image plane is collected back into the
20   waveguide by confocal imaging. The light collected in the
cladding of the waveguide has a higher numerical aperture
than the light collected in the core. The cladding light is
detected by a mode-stripping detector. As such, the system
of the present invention provides a dual numerical aperture
25   confical detection system. Techniques for combining a
cantilevered waveguide, a drive, motion sensors and a mode-
stripping detector using microelectromechanical systems
(MEMS) technology are described.

30   The device of the present invention provides for a
cantilevered waveguide, transducer, detector and electronics
to be combined using silicon-based MEMS technology. This
integration of the main system components provides for the

construction of a cheap, reliable bar code reader based on
these principles. Because silicon is not a direct gap
material, the source cannot be integrated. However, it may
be added by hybrid integration of a discrete laser in III-V
5   materials. Generally, the source will emit visible light to
allow the scanner to be pointed by eye.

It will be appreciated that components of the present
invention have been shown and described in specific
10   combination with one another. It is not intended to limit
the present invention to any one specific combination and it
will be appreciated that any one component may be taken and
combined with any other component without departing from the
spirit and scope of the present invention. It is not
15   intended to limit the present invention except as may be
required in the light of the appended claims.

The words "comprises/comprising" and the words
"having/including" when used herein with reference to the
20   present invention are used to specify the presence of stated
features, integers, steps or components but does not
preclude the presence or addition of one or more other
features, integers, steps, components or groups thereof.